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Particle Entrainment Simulator at the U.S. Army Engineer Research and Development Center

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PURPOSE: This technical note describes the particle entrainment simulator (PES), which is used at the U.S. Army Engineer Research and Development Center (ERDC) for experimental determination of erodibility of fine-grained cohesive sediments. The device, its method of operation, experimental data reduction, and application of PES results to studies related to estuarine and coastal sediment transport problems are briefly described.

BACKGROUND: Prediction of fine-grained sediment erosion must be based on hydrodynamic forces at the site and erodibility characteristics of the in situ material. Determining the erodibility of fine-grained cohesive sediment is much more difficult than for the coarse-grained sediments. Equations available for predicting transport of noncohesive sediments use grain-size and physics-based descriptors. The present state of the art for cohesive sediment transport prediction involves several empirical coefficients in mathematical description of sediment dynamics processes. Teeter (1990), Mehta (1992), and Parchure et al. (2003) described the physico-chemical factors and parameters involved in cohesive sediment dynamics. The values of empirical parameters must be determined from experimental results or estimated based on available literature on sediments similar to those prevailing at the site under consideration. Estimates of erodibility parameters can be made using basic characterization information in some cases. Erosion at a given site also depends on the depositional properties of sediment, bioturbation, and history of flow-induced shear stresses. Therefore, the local hydrodynamic and biochemical conditions as well as sediment properties at each site need to be well understood.

Conducting experimental erosion tests is an integrated method of characterizing cohesive sediments in terms of their erodibility assessment. However, erosion-testing procedures are not standardized, and a variety of laboratory and field approaches and devices are available. Lee and Mehta (1994) described several laboratory and field devices used for measuring cohesive sediment erosion. Subsequently, more devices have been added such as the SEDflume (McNeil et al. 1996) for unidirectional, high shear stress flow and the Sediment Erosion Actuated by Wave Oscillations and Linear Flow (SEAWOLF) Flume (Jepsen et al. 2003). Most of the devices are specialized equipment and are expensive and time-consuming to use. Currently used simple erosion testing devices involve a few assumptions about hydrodynamic and/or sediment conditions. The PES is one such device. It has been developed, tested, and used by several investigative groups in the United States to determine the erodibility of undisturbed, fine-grained surface sediment samples. The PES provides a practical and inexpensive method for cohesive sediment characterization. It is also a tool that has potential for wider use in the laboratory and in the field.

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Rouse (1938) employed for the first time a device with vertically oscillated grids for generating zero-mean-shear turbulence in sediment resuspension experiments. Subsequently Murray (1969) simulated sediment resuspension using oscillating grids. Tsai and Lick (1985, 1986) developed an oscillating disk device (Figure 1) for investigating Great Lakes sediment resuspension. The calibration curve for the device is given in Figure 2.

Subsequently, Lavelle and Davis (1987), Bokuniewicz et al. (1991), and Davis (1993) have used copies of the device. The PES has been used at the U.S. Environmental Protection Agency's Environment Research Laboratory at Narragansett (ERLN), Rhode Island (Lavelle and Davis 1987; Latimer et al. 1999), and University of Florida, Gainesville, Florida (Rodriguez et al. 1997). At ERDC, the basic PES design was adopted and refinements were made to the hardware, data acquisition system, and data analysis.

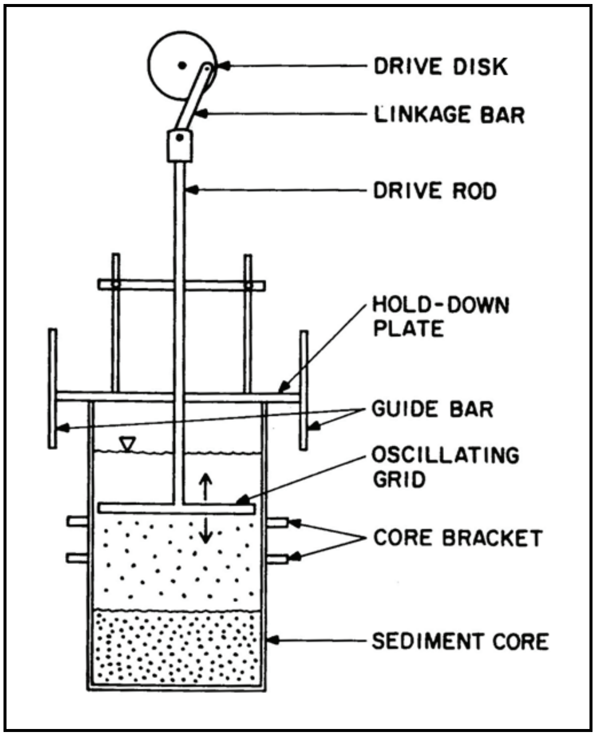


Figure 1. Schematic diagram of the device used to entrain sediments (Tsai and Lick 1985)

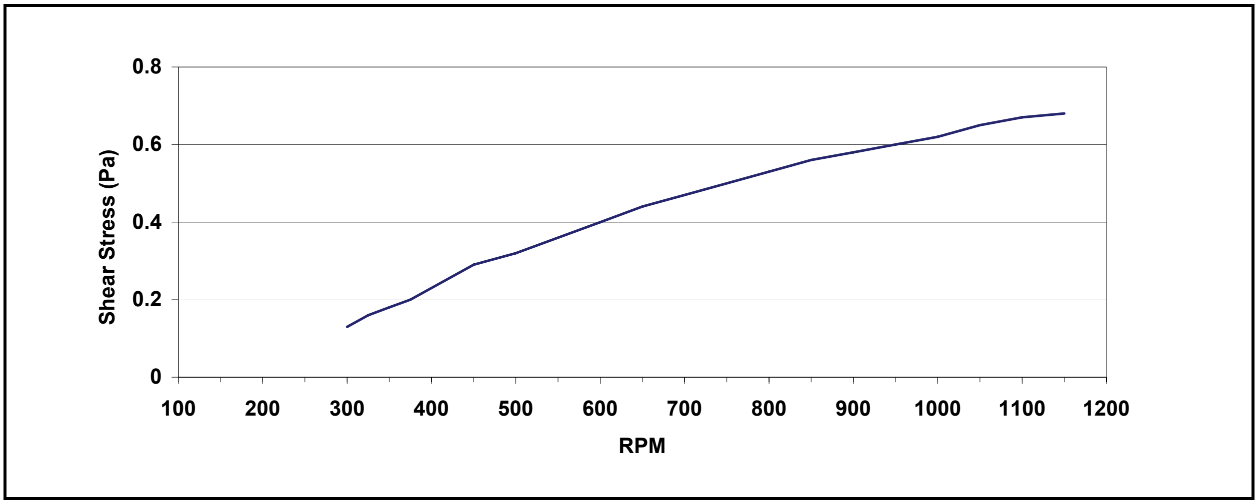


Figure 2. Empirical relationship between disk oscillation frequency and equivalent bottom stress used at ERDC

Oscillating-grid turbulence devices have been used in problems of entrainment of fluids across density interfaces (Rouse and Dodu 1955; Cromwell 1960; Turner and Kraus 1967). The turbulence structure within oscillating grid chambers has been extensively studied through measurements and theoretical development (Bouvard and Dumas 1967; Thompson and Turner 1975; Hopfinger and Toly 1976; McDougall 1979; Xuequan and Hopfinger 1986; Long 1978; Orlins 1996). Dependence of turbulence on the oscillation frequency, distance from the grid, stroke length, and mesh size as well as mesh-form have all been investigated. While it is clear that the turbulence field generated by such a device is different than that generated by a shear flow, corresponding conditions can be found for which entrainment rates that depend on the instantaneous turbulence stresses in the boundary layer in both types of flow can be made identical.

DESCRIPTION: The PES fabricated at ERDC is a portable device with an erosion chamber geometry identical to that used by several other investigators. It requires only about a 1-m by 1-m table space and 600 W of 120-V alternating current power. The main unit weighs 25 kg. It is designed to serve as a laboratory/field tool for erodibility assessment of undisturbed cohesive sediment core sections. A schematic drawing is shown in Figure 3. Photographs of the PES and the grid are shown in Figures 4 and 5.

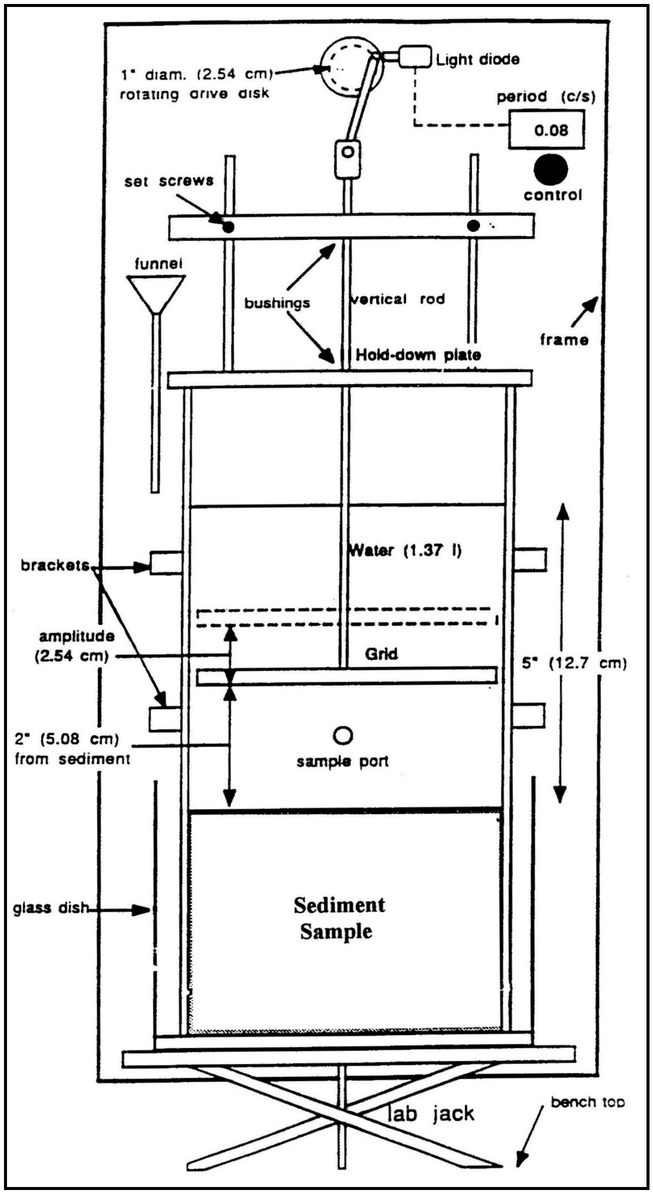
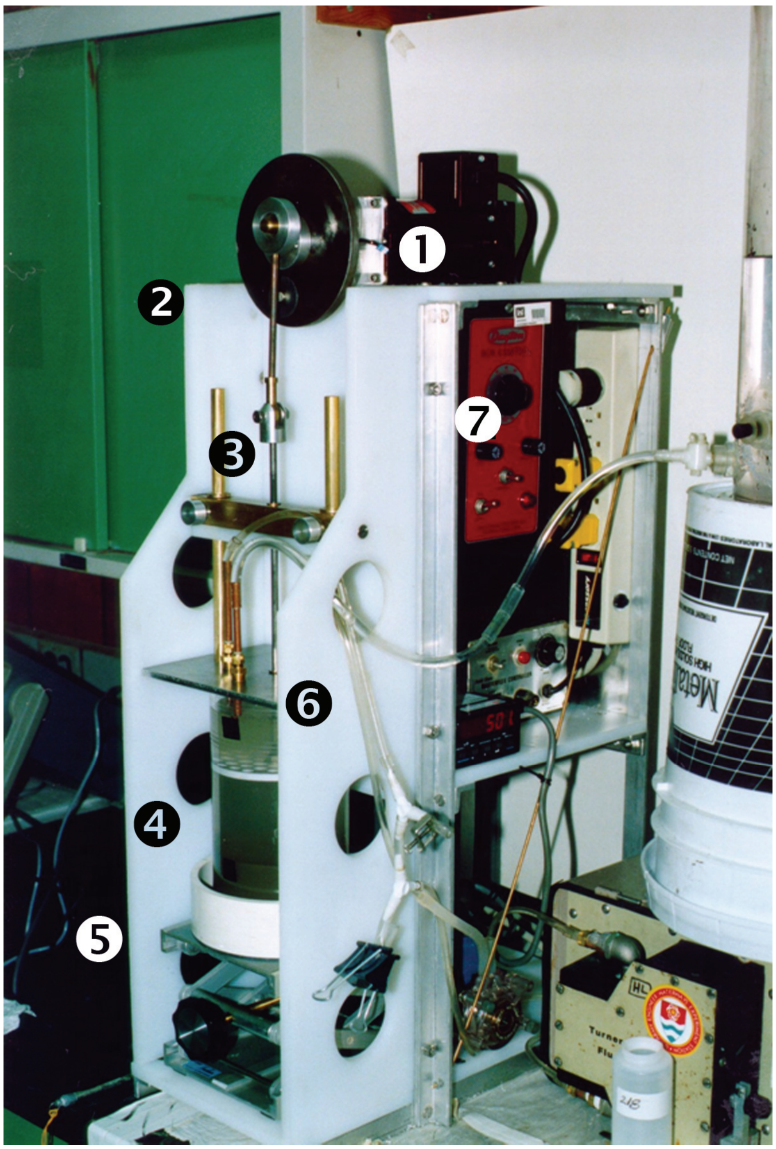


Figure 3. Schematic layout of PES at ERDC

The erosion chamber is a vertical Plexiglas cylinder, 30 cm in height with 11.70 cm inside diameter. It is held firmly between a bottom platform and an adjustable horizontal plate at the top. A 0.6-cm-thick perforated horizontal Plexiglas disk is concentrically placed inside the cylinder to move within a 13-cm-high fluid column overlying the sediment. The 11-cm-diam disk with 1.2-cm-diam holes is connected to a variable speed motor at the top by means of a vertical rod. The distance between the centers of two adjacent holes is 1.5 cm. The porosity of the grid is 42.8 percent. The disk is located at a minimum distance of 5 cm above the sediment bed and has an excursion of 2.54 cm. The water level is kept at 13 cm and the mean bed elevation is 6.3 cm. The vertically oscillating grid generates turbulence above the sediment to simulate the erosive bed shear stress. Samples of

suspended sediment can be withdrawn from the erosion chamber for determining concentrations. The mean bed shear stress, normally used to correlate erosion, is not available as a measurable parameter. The PES was originally calibrated by comparing suspension concentrations obtained with PES to those from an annular flume. Identical sediments and bed-preparation procedures were used in both devices. It was assumed that identical suspension concentration values are achieved under identical shear stresses in both devices. This assumption was used to correlate the oscillation rate in PES to the equivalent shear stress values of the flume. Each newly fabricated PES unit must be calibrated by using another reliable erosion device.



1. Drive motor
2. Main frame
3. Grid oscillating rod
4. Sediment bed in cylinder
5. Adjustable platform
6. Suspension withdrawal tubes
7. Speed controller

Figure 4. Photograph of PES

FIELD SAMPLE COLLECTION: The PES can be used onboard a vessel, which is typically longer than 11 m. For small boat operations, the PES could be set up onshore in a truck or building with easy access to a boat landing. The PES sample is obtained as a subsample from another sampling device. Lavelle and Davis (1987) used a 21-cm by 30-cm box core to obtain samples from large boats. From small boats, a 15-cm box core has been used to obtain samples. The PES subsamples are taken from the box sample immediately after the sample is onboard and stored at low temperature. Instead of bringing the sediment sample to the laboratory, the PES has also been used in the field on a ship to test erodibility of fresh, undisturbed 5-in.-diam (12.7-cm-diam) subsamples taken from a box core.

Figure 5. Perforated disk (grid) and suspension withdrawal tubes of PES

Typically, a sediment sample is acquired by standard box core with surface dimensions of about 20 cm by 30 cm. Flaps on the corer near the top of the box are closed as the core is pulled out of the bottom, thus limiting the disturbance of the surficial sediment as the core is raised to the water surface. On deck, two subsamples (plugs) from each core are carefully taken by partially inserting lengths of 13-cm-diam acrylic pipe into the core. Locations of these plugs of sediment within each box are chosen to avoid box edges, to capture material representative of the surface, and to avoid any visible disturbance resulting from the coring. Bottom caps are slid under the tubes that are partially filled with sediment. The volume overlying the sediment is then filled with site water, top caps installed, and each plug securely stored.

OPERATIONAL PROCEDURE: The sample tube is placed on a platform that can be moved vertically for adjusting the tube elevation. The PES operation essentially consists of adjusting the oscillation frequency of the grid to the desired level, running the device for a preplanned duration of time, and collecting water samples from the erosion chamber at predetermined time intervals. PES tests often start at 100 rpm or about 0.1 Pa and continue to about 900 rpm corresponding to 0.6 Pa. The disk is run for the first 2 min at very low rpm to bring into suspension very loose sediment lying on the bed surface that may be a result of bed preparation inside the cylinder. The sediment suspension is discarded and the erosion chamber filled again with eroding fluid. The shear stresses are typically stepped up in increments, allowing 30 min of running at each step for the sediment to erode. During each shear stress step, subsamples of the

supernatant are drawn over time through a side port in the acrylic tube walls. At the end of each time step, the chamber fluid volume is replaced with particle-free water to keep the water level constant in the erosion chamber. Some researchers have used optical devices for determining suspension concentration. Davis (1993) measured turbidity of subsamples with a Bausch and Lomb spectrophotometer model Spectronic 20 using a wavelength of 660 nm and then converting to suspended solids concentration through a sediment-specific empirical relationship.

At ERDC the suspension concentration is determined by filtering the samples through 0.45-μ polycarbonate Nuclepore filters. Because the volume of the PES erosion chamber is low, the suspension concentrations are adjusted for the sediment withdrawn during sampling. This adjustment is made by numerically adding the amount of sediment removed during sampling to the results of suspension concentration of the subsequent samples.

Ideally, undisturbed in situ bed samples should be used for determining erosion rates. However, laboratory devices generally use molded or redispersed-and-deposited test sediment beds for conducting erosion tests. When slurries are settled to form a deposited test bed in the chamber, the elevation of the sediment-water interface is measured immediately after pouring the slurry and again before each erosion test. Varying consolidation times are used before beginning the erosion tests. Varying the consolidation times results in varying bulk densities and shear strengths of the bed. It is essential to determine the bulk density of the sediment bed as a function of sediment depth for determining erosion rate. It is best to perform erosion experiments at shear stresses that correspond to the anticipated field conditions. ERDC developed a modified operational procedure that provides information needed for use in the numerical erosion models used for sediment studies of various projects. The procedure adopted at ERDC for operation of the PES is given below with enough detail to enable use of PES by new users.

DATA REDUCTION: The basic information from PES tests is suspended sediment concentration as a function of time over specific grid oscillation rates, which represent corresponding bed shear stresses. Final slurry volume concentration and bulk wet density (BWD) are calculated from the data on the initial and settled sediment thicknesses, and the initial slurry volume concentration. From the measured bulk bed density and the results of suspension concentration, the mass of sediments eroded from bed surfaces is calculated. Erosion rates are calculated as a function of time and bed shear stress values. Each shear stress step is analyzed by regression analysis to determine erosion rate. Acceleration at the beginning of each shear stress step produces a time-varying component of shear stress. To avoid this, regression is performed on adjusted concentrations at 10 to 30 min of each step. Regression results are considered acceptable if p-values are less than 0.20. This procedure eliminated results with near-zero slopes and marginal regression fits. The final data analysis step involves use of a specific erosion equation. This equation may or may not include the value of critical shear stress for erosion. In any case, estimated erosion rates and corresponding shear stresses along with bed density or other parameters are used to fit empirical coefficients by regression analysis.

APPLICATIONS: The PES has been used at ERDC to assess the erodibility of three general types of sediments:

- Bed sediments from water bodies such as lakes, rivers, and reservoirs.
- Navigation channel bottom sediments.
- Sediment slurries used to simulate the dredging and disposal processes.

The first type of sediment is usually involved in investigations of general sediment transport, while the latter two types are involved in investigations of sediment transport associated with Corps of Engineers dredging and disposal operations. Natural bottoms generally have moderate to high BWD and can be fine-grained or contain substantial fractions of sand-sized particles. These sediments are handled and tested in such a way as to minimize disturbance.

Channel bottom sediments from most estuarine channels are predominantly fine-grained with substantial clay fractions, and have low BWD's. Erosion tests are performed on undisturbed sediments, or, if appropriate, on remolded sediment composites or other types of sediment samples. It is always desirable to test sediments under conditions closely resembling those in the field, including undisturbed sediment deposits. Sediments undergo appreciable disturbance during dredging and disposal, and a remolded channel sediment sample, after appropriate aging, may be representative of the fully recovered erodibility of these sediments. If sediments are composited and remolded, an appropriate time must be allowed for recovery of shear strength, representative of field conditions in which sediments are dredged and placed. In some cases this may not be possible. For navigation channel sediments, which are disturbed by the effects of vessel passage, judgment must be exercised in simulating the laboratory sediment beds for conducting erosion experiments.

The dredging and disposal processes tend not only to disturb sediments, but also to mix them with ambient water. Mechanical dredging methods disturb the bed sediments, while hydraulic and hopper dredge operations result in mixing and dilution of sediments with ambient water. Further disturbance of sediment bed and dilution of suspended sediment with ambient water may occur, depending upon the site conditions and the disposal methods. Short-term effects of dredging and/or disposal on the shear strength and erodibility of sediments were simulated in an ERDC laboratory by preparing a slurry of sediment and water in ratios of 1:2 to 1:4. The slurry was allowed to settle and consolidate before conducting erosion tests. Settling times were varied from a few hours to a few days. Samples were tested as early as 1 hr after preparing slurry, but rapid settling continued during the experiment, which caused difficulties in maintaining proper geometry between the PES disk and the sample bed.

Self-weight consolidation with time leading to increased shear strength is an important property of cohesive sediments. Therefore, laboratory test beds are frequently prepared with several different settling times starting from 1 day. For experiments on sediments from approach channels to Baltimore Harbor (Johnson et al. 1999), slurries were allowed to settle for 1 to 8 days before testing. For slurried channel sediments from the Port of New York/New Jersey (Chou et al. 1998) and from the Gulf Intracoastal Waterway at Laguna Madre, TX (Teeter et al. 2002), consolidation continued up to 21 days. It is desirable to perform replicate erosion experiments to assess and compensate for variability in erosion results due to sediment variability and/or experimental procedures. Variability of 20 to 30 percent is typical for natural sediments,

although replicate tests on uniform model sediments have had a variability of less than 10 percent. Parchure (2003) complied results of erosion experiments conducted by using PES on sediments collected from several project sites in the United States.

Examples of PES applications at ERDC to assess bed sediment erodibility include the Sudbury Project (Nail and Abraham 1998), Ashtabula Project (Teeter et al. 1999), and Upper Mississippi River (Copeland et al. 2001). Other agencies have used the device for similar applications, as reported by Davis (1993), Davis and Abdelrhman (1992), Davis and Means (1989), Lavelle and Davis (1987), MacIntire et al. (1990), Sfrisco et al. (1991), Ziegler et al. (1987), and Mehta et al. (1997).

The most commonly used erosion rate equations used in numerical models are (Mehta and Parchure 2000):

$$E = M\left[\frac{\tau_b - \tau_c}{\tau_c}\right] \tag{1}$$

$$E = A\left[\frac{\tau_b - \tau_c}{\tau_c}\right]^B \tag{2}$$

where

E = erosion rate (g/cm2/sec)
M = erosion rate constant (g/cm2/sec)
τ_b = bed shear stress (Pa)
τ_c = critical shear stress for erosion (Pa)
A = empirical coefficient (g/cm2/sec)
B = Empirical coefficient

Flow-induced or wave-induced bed shear stress can be calculated for the given site conditions; however, at present, the magnitude of critical (threshold) shear stress for erosion and the values of empirical coefficients included in these equations can be determined only through laboratory tests conducted on field sediment samples. The effect of consolidation also needs to be determined in a laboratory. For determining the critical bed shear stress inside the PES cylinder, the oscillation frequency of the perforated disk is increased from zero in small increments. The sediment-fluid interface is observed throughout the frequency increase. The frequency at which erosion is observed to commence at the interface is converted to shear stress value from the PES calibration curve. This shear stress is the critical shear stress value for erosion for the type of bed simulated inside the PES cylinder. An illustration of results obtained with use of PES is given in Figures 6 and 7. Figure 6 shows erosion threshold versus settling time for field sediment samples collected from NY/NJ Harbor. Figure 7 shows erosion rate as a function of bed shear stress. The magnitudes of M in Equation 1 or the values of empirical coefficients can be determined from the two plots.

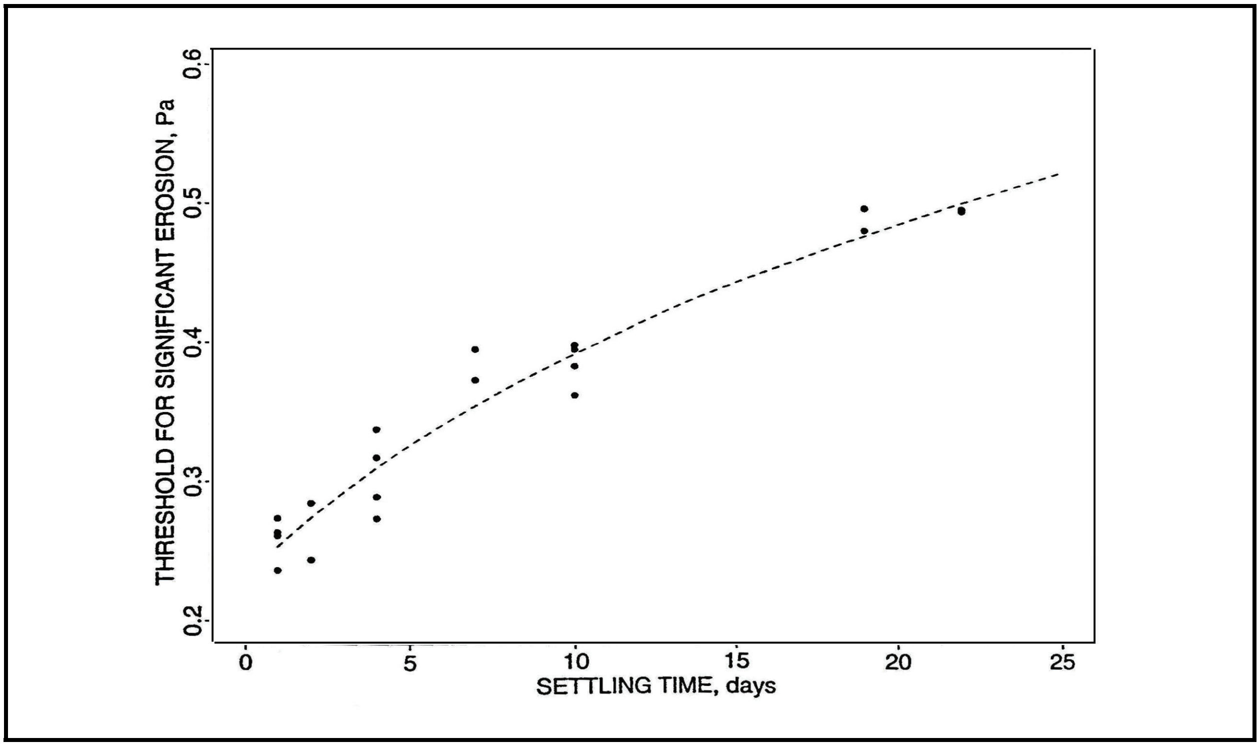


Figure 6. Erosion threshold versus slurry settling time for NY/NJ Harbor sediment samples (Teeter 1998)

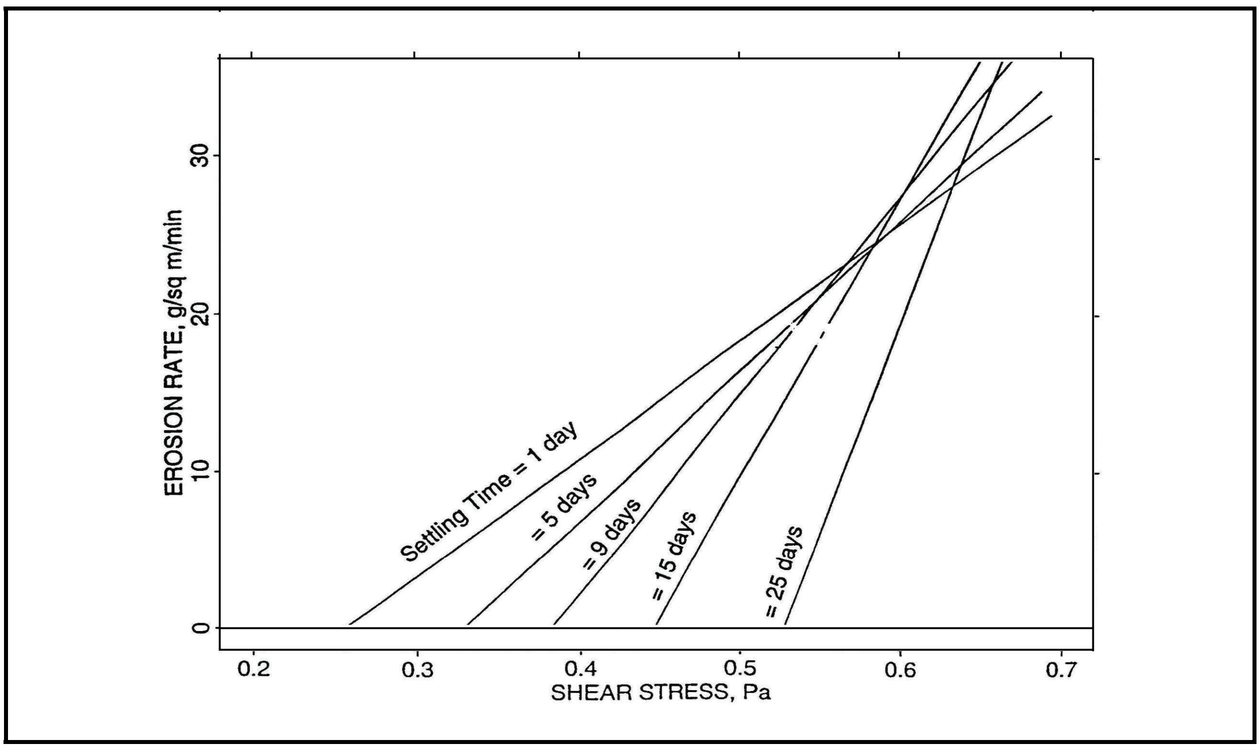


Figure 7. Erosion rate versus bed shear stress for NY/NJ Harbor sediment samples (Teeter 1998)

Illustrative test results are given below:

a. Sudbury River (Nail and Abraham 1998). Critical shear stress for erosion: 0.2 Pa; erosion rate at bed shear stress of 0.4 Pa: 0.002 kg/m^2/min; erosion rate at bed shear stress of 0.6 Pa: 0.01 kg/m^2/min.

b. Ashtabula River (Teeter et al. 1999). The bed sediment was classified as clayey-sandy silt. The silt content varied between 42 and 72 percent and the clay content varied between 15 and 30 percent. The sediment was partially consolidated with wet bulk density varying between 1.44 g/cu cm and 1.54 g/cu cm. The critical shear stress for erosion varied from 0.2 to 0.28 Pa. The erosion rate constant varied from 7.22 to 10.0 g/sq m/min.

Limitations are as follows:

a. Oscillating-grid turbulence devices have been used in problems with entrainment of fluids across density interfaces, and the turbulence structure within oscillating grid chambers has been extensively studied through measurements and theoretical development. However, since adequate mathematical treatment is not available specifically for the mechanism of inducing bed shear stress PES, the actual bed shear stress as a function of grid characteristics and oscillation frequency cannot be calculated. This relationship has to be indirectly estimated by adopting comparative calibration techniques. Each newly fabricated PES unit must be calibrated before its intended use.

b. The maximum bed shear that can be induced in PES is approximately 0.6 Pa, which may not be adequate for eroding consolidated sediments.

c. PES is suitable only for cohesive sediments. It cannot be used to determine erosion rates of noncohesive sediments, which do not distribute uniformly over the water column due to high settling rates.

AVAILABILITY OF PES TO CORPS USERS: The ERDC PES is available for loan to Corps of Engineers Districts. Sediment samples collected in the field can be analyzed at the well-equipped, state-of-the-art sediment laboratory at ERDC, and a report on the laboratory results can be furnished.

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ADDITIONAL INFORMATION: For additional information, contact Dr. Joe Gailani (601-634-4851, Joe.Z.Gailani@erdc.usace.army.mil) or Trimback M. Parchure (601-634-3213, Trimback.M.Parchure@erdc.usace.army.mil). The study was conducted as an activity of the System-Wide Water Resources Program (SWWRP). For information on SWWRP, please consult https://swwrp.usace.army.mil/ or contact the Program Manager, Dr. Steven L. Ashby, at Steven.L.Ashby@erdc.usace.army.mil. This technical note should be cited as follows:

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